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Design and fabrication of an angle of repose apparatus for granular material analysis

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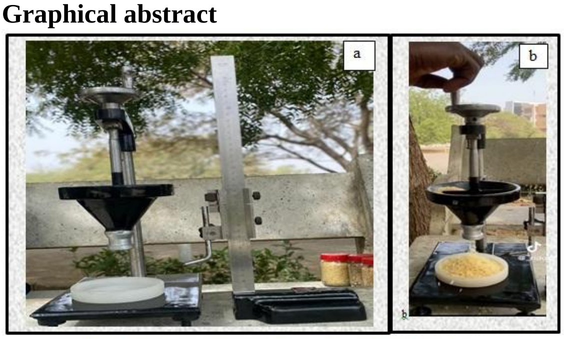
ABSTRACT

The angle of repose (AOR) plays a crucial role in analyzing the flowability of granular materials, which are widely used in fields such as agriculture, pharmaceuticals, and civil engineering. This study outlines designing and constructing an affordable, user-friendly Apparatus for accurate AOR measurement. Built for both laboratory and field applications, the Apparatus was made from materials that are easily accessible and include an adjustable funnel, a central column, and a sturdy base to ensure consistent and precise measurements. Experimental tests using agricultural materials such as rice, beans, wheat, and millet yielded reliable results with low standard deviations. A paired t-test indicated significant statistical differences between the newly designed Apparatus and conventional methods (t-statistic of -2.98, p-value of 0.015), though these differences fell within an acceptable experimental range of ±0.5°. The mean difference of -0.26° and a 95% confidence interval of [-0.43°, -0.09°] illustrate a slight downward bias in the Apparatus while confirming its reliability and accuracy. This research provides a practical solution for measuring AOR, especially in resource-constrained environments, and suggests potential enhancements, like incorporating digital sensors for greater precision and changeable orifice opening sizes for the funnel ranging from 10 mm to 22 mm.

Keywords: Angle of repose; granular materials; flowability; measurement apparatus; agricultural materials; experimental validation.

Graphical abstract



(a) Full view of the Apparatus; (b) Testing the AOR of rice grain

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1. Introduction

The angle of repose (AOR) is a critical parameter for characterizing the flowability of granular materials such as seeds, grains, and powders. When granular solids form a pile on a flat surface, the sides of the pile maintain a reproducible angle with the horizontal surface, known as the angle of repose [1]. This parameter is widely utilized across various fields, including pharmaceutical manufacturing, agriculture, and civil engineering, as it provides valuable insights into the flow characteristics of materials. Understanding AOR is essential for designing equipment, optimizing grain handling processes, and developing storage solutions tailored to specific material properties. These applications underscore its importance in improving efficiency and minimizing risks associated with handling granular materials.

AOR is influenced by several physical properties of materials, including particle size, shape, and surface characteristics [2]. Smooth, round particles generally exhibit a lower angle of repose, indicative of higher flowability. In contrast, fine or sticky materials display higher angles, requiring additional handling to prevent blockages. For instance, agricultural grains like wheat and rice, which tend to have relatively smooth surfaces, are easier to handle than powders or biomass pellets with irregular shapes or adhesive properties. The flowability of materials with low AOR often allows them to be transported using gravitational force or minimal energy [2], while those with high AOR demand more sophisticated handling systems, such as mechanical feeders or pneumatic conveyors.

Accurately measuring the AOR is challenging due to variability in material properties and inconsistencies in measurement methodologies. Traditional techniques, such as the ASTM International and Cornforth methods, rely on assumptions about symmetrical pile shapes, leading to variability in results. For example, differences of up to 35% have been reported between measurements obtained using these methods [3]. These methods, while widely used, are limited in their ability to account for irregular pile shapes, which are common in real-world applications. Similarly, manual techniques, including protractor measurements and trigonometric calculations, often introduce subjective biases, further compounding the issue of reproducibility [4].

Such inconsistencies have significant implications, For larger granular materials, such as biomass pellets, there is a need for standardized measurement procedures to ensure reproducibility [5]. For example, in the agricultural sector, the design of storage facilities like bins, hoppers, and silos depends on precise AOR values [6]. An inaccurate AOR measurement can result in inefficient designs, leading to flow blockages, material waste, or structural failures. Likewise, in pharmaceutical manufacturing, where powders with varying flow properties are processed, measurement inconsistencies can disrupt production workflows and compromise product quality.

To address these limitations, researchers have explored more precise and reproducible measurement methods. An automated digital image processing algorithm using maximal least square regression was developed to improve the accuracy of AOR measurements [7]. This method eliminates the subjectivity associated with manual measurements and accounts for irregular pile shapes, offering a significant improvement over traditional techniques. Additionally, a validated measurement system using Nested Gage Repeatability and Reproducibility has been introduced to further reduce errors and enhance consistency in AOR determination [8]. However, these advanced approaches are often inaccessible to resource-limited laboratories due to their cost and complexity, limiting their widespread adoption.

Recognizing these challenges, this study aims to design and fabricate a cost-effective, user-friendly apparatus for measuring the angle of repose. By leveraging readily available materials with straightforward fabrication techniques, the proposed apparatus seeks to address the limitations of traditional methods while ensuring accessibility for educational settings, small-scale laboratories, and field applications. This apparatus is designed to deliver reliable and accurate measurements without requiring specialized training or expensive equipment. By bridging the gap between traditional and advanced methodologies, the study aims to provide a practical solution to improve the reproducibility and applicability of AOR measurements in diverse settings.

The apparatus has already been donated to the Crop Processing Lab at Bayero University Kano, Department of Agricultural and Environmental Engineering, where it is being utilized by students for practical experiments, demonstrating its accessibility and utility in educational settings.

2. Materials and Methods

2.1 Design Specifications

The Apparatus was accurately designed to prioritize precision, practicality, and innovation, addressing limitations commonly associated with traditional angle of repose (AOR) measurement devices. Key design elements include a stable high-density fiberboard (HDF) base, a central column with adjustable height settings, a stainless-steel funnel, a steering mechanism, and a granular material collector. A carefully dimensioned HDF base (220 mm x 160 mm x 14 mm) enhances the Apparatus's stability, ensuring minimal vibration during experiments. The 20 mm diameter rod's central column allows for adjustable configurations, providing flexibility to accommodate varying material types. The stainless-steel funnel, with an orifice diameter of 13 mm, ensures a controlled flow of granular materials. At the same time, the steering mechanism prevents clogging and promotes even material distribution within the funnel.

Traditional AOR devices often lack height adjustability, leading to inconsistent heap formation and limited adaptability to different granular materials. Additionally, clogging during material flow is common due to the absence of mechanisms to dislodge stuck particles. This Apparatus addresses these challenges through a height-adjustable funnel and a spade-like steering mechanism, ensuring uniform material flow and reliable results.

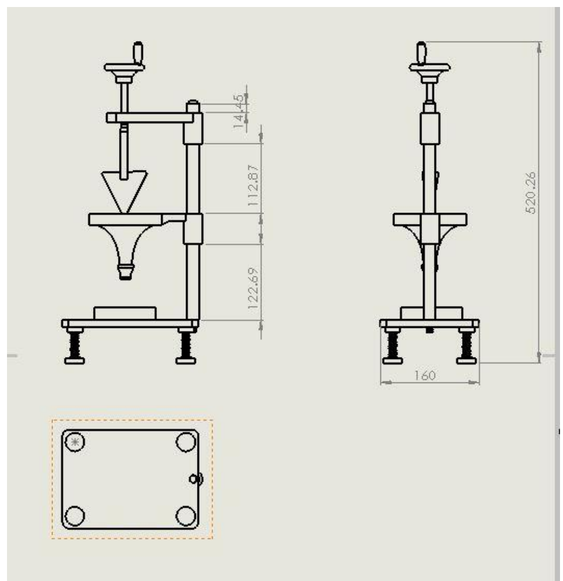

Fig 1. Assembly detailed drawing of the apparatus

2.2 Fabrication Process

The Apparatus was fabricated using precision manufacturing techniques and carefully selected materials to ensure reliability and durability. The process involved multiple stages, each emphasizing accuracy and innovation.

Unlike traditional fixed setups, which are likely to rigidity and limited flexibility, this Apparatus employs an integrated design that allows for precise height adjustments and easy replacement of individual components. This feature ensures adaptability for granular materials and experimental conditions, improving usability and reproducibility.

2.2.1 Base Construction

The HDF base was cut from an 8-foot by 8-foot board to precise dimensions (220 mm by 160 mm) using a bandsaw, square, and measuring tape. This stage ensured consistent and straight edges. Holes were drilled strategically to secure the attachment of adjustable feet and precise tapping using an M14 tap threads with a 2 mm pitch. These detailed adjustments enhance the apparatus's stability and alignment.

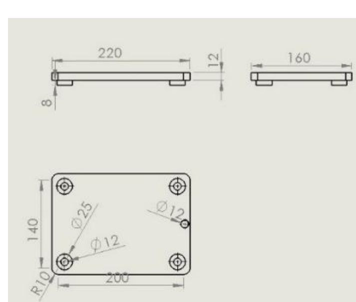

Fig 2. Base detailed drawing

2.2.2 Adjustable Feet

The adjustable feet, fabricated from a 30 mm diameter rod, were machined precisely on a lathe. Each foot was step-turned to a diameter of 13.8 mm and threaded to ensure compatibility with the tapped base. Vernier caliper for verification and the consistent 8 mm length of each foot contribute to uniformity and balance, ensuring the Apparatus remains level even on uneven surfaces. This attention to detail minimizes errors during AOR measurement.

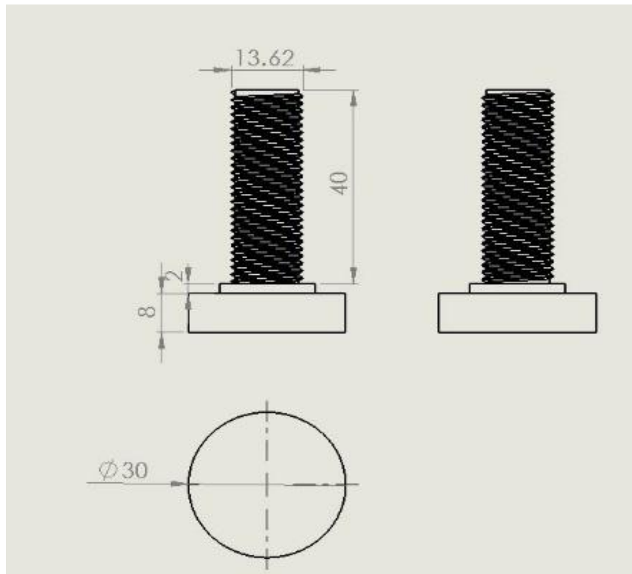

Fig 3. Adjustable feet detailed drawing

2.2.3 Column and Support Structure

The main column, crafted from a 20 mm diameter rod cut to a length of 380 mm, was further machined to secure assembly with the base. Additional components, including two 30 mm diameter pipes, were designed to slide along the column, offering adjustable height settings for the funnel. These pipes were tapped with M6 threads and could be securely locked using M6 bolts, ensuring stability and adaptability for varying granular material types. This design element is particularly novel, as it allows precise height adjustments without requiring disassembly.

Traditional AOR devices typically feature fixed columns, restricting their ability to adapt to varying material properties. The adjustable column in this design enables precise height configurations, enhancing flexibility and accuracy during experiments.

2.2.4 Funnel and Steerer Assembly

A 13 mm orifice diameter stainless-steel funnel was integrated with a larger machined pipe, providing both durability and precision in controlling material flow. A key innovation in this assembly includes a spade-like steerer mechanism designed to dislodge lodged materials and ensure even distribution. The steerer, fabricated from a combination of chamfered rectangular rods and plates, enhances the Apparatus's functionality by preventing flow interruptions and enabling consistent results across various granular materials.

Conventional designs frequently experience clogging and uneven flow distribution, resulting in variability and errors. The spade-like steerer mechanism integrated into this Apparatus ensures smooth and consistent material flow by dislodging stuck particles and evenly distributing granular materials, addressing a common limitation in traditional setups.

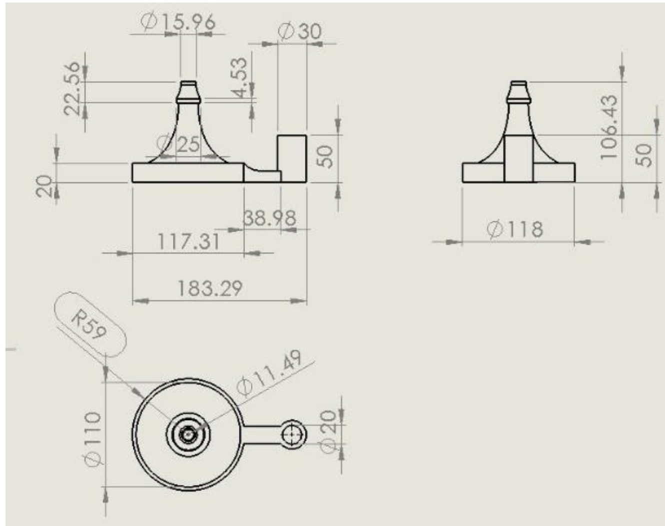

Fig 4. Funnel detailed drawing

2.2.5 Steerer Mechanism

The steerer mechanism represents a significant advancement in the design of AOR measurement devices. A rectangular rod, precision-machined and chamfered, houses a steerer bearing that facilitates smooth movement. This innovative design prevents contact with the funnel interior, reducing friction and ensuring unobstructed material flow. Additionally, the spade-like steerer, welded to the rod, evenly distributes granular materials, further enhancing the reliability and reproducibility of measurements.

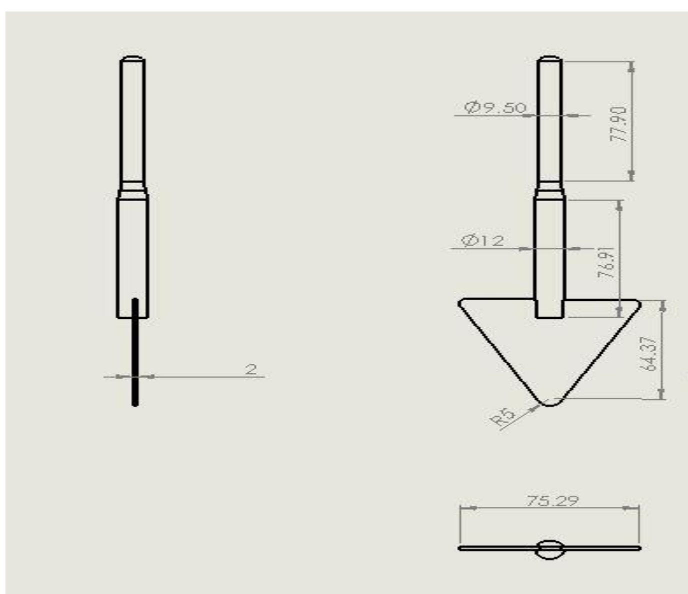

Fig 5. Steering detailed drawing

2.2.6 Granular Material Collector

The granular material collector, crafted from a Teflon rod, ensures consistency in heap formation by maintaining a constant diameter of 90 mm. The blind-bored collector minimizes static interference and is specifically designed to produce uniform heaps, addressing a common limitation in traditional AOR measurement setups. This precision enables highly reproducible results, even in challenging experimental conditions.

Due to inconsistent material collection processes, traditional AOR devices often fail to produce uniform heap dimensions. This Apparatus incorporates a Teflon granular material collector designed to maintain a constant heap diameter of 90 mm, minimizing static interference and ensuring reproducibility.

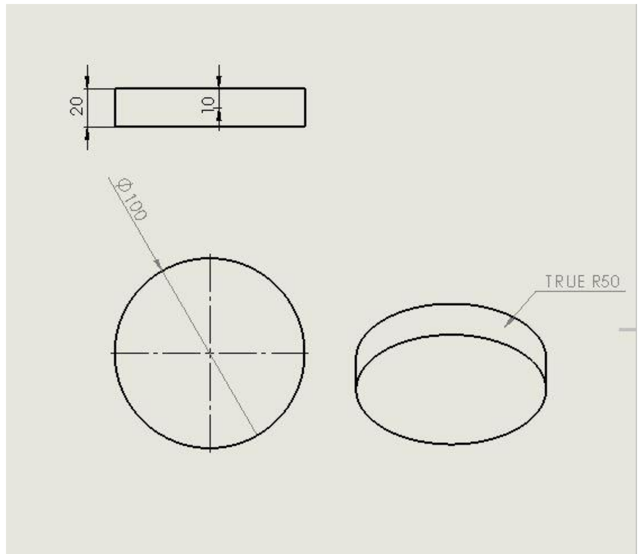

Fig 6. Material collector detailed drawing

2.2.7 Handle Fabrication

The steering handle was ergonomically designed to enhance operator comfort and control. Fabricated from a 65 mm diameter rod, the handle facilitates smooth adjustments to the steering mechanism, allowing operators to maintain consistent flow rates during experiments. This feature underscores the apparatus's practicality and usability.

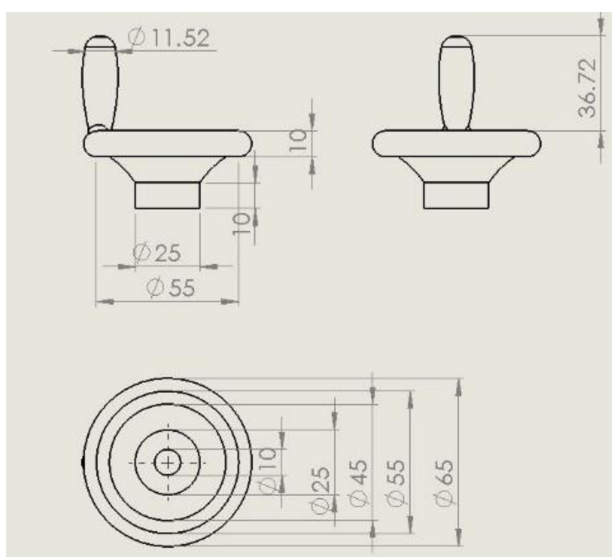

Fig 7. Handle detailed drawing

2.3 Experimental Setup

The experimental setup was accurately calibrated to ensure accuracy. The base was leveled using the adjustable feet, and the central column was aligned vertically. The funnel height was adjusted based on the tested granular material, ensuring optimal conditions for each experiment. The steerer mechanism was positioned to avoid contact with the funnel interior, maintaining unobstructed flow. A Teflon collector was placed beneath the funnel, guaranteeing consistent heap dimensions. This setup highlights the Apparatus's adaptability and precision in accommodating diverse granular materials.

Traditional experimental setups often require extensive manual calibration to achieve stability, leading to variable results. This Apparatus addresses these issues with adjustable feet and precise alignment features, ensuring consistent leveling and repeatable experimental conditions.

2.4 Procedure

1. **Material Preparation:** A consistent quantity of granular material was selected and measured to ensure repeatable results.
2. **Apparatus Setup:** The apparatus was placed on a stable surface, and the adjustable feet leveled the base. The funnel height was adjusted as required.
3. **Steerer Calibration:** The steerer mechanism was carefully positioned to ensure free movement of granular material within the funnel.
4. **Testing:** Granular material was gradually released from the funnel, with the steering handle used to ensure even distribution and prevent clogging.
5. **Measurement:** Once a stable heap was formed, the height and diameter of the heap were measured to calculate the angle of repose using the formula:

$$\theta r = \tan^{-1}\left[2\frac{(Hc - Hp)}{Dp}\right]$$

Where,

Hc = height of cone from datum.

Hp = height of platform.

Hc - Hp = height of cone of solids.

Dp = diameter of circular platform.

Θr = angle of repose.

The procedure ensures consistency in measuring the angle of repose by standardizing material preparation, apparatus setup, and testing. Potential sources of experimental error include operator handling, variability in granular material properties, and environmental conditions such as humidity or vibration.

2.5. Experiment Site

The experiments were conducted in the Crop Processing Laboratory of the Department of Agricultural and Environmental Engineering, Bayero University Kano. The laboratory's controlled environment provided ideal conditions for conducting careful and repeatable experiments. Figure 1 illustrates the experimental setup, showcasing the apparatus in use and emphasizing its practical application.

Fig 8. (a) Full view of the Apparatus; (b) Testing the AOR of rice grain

3. Results and Discussion

The experiments conducted using the fabricated angle of repose (AOR) apparatus demonstrated its effectiveness in accurately measuring the angle of repose for a variety of granular materials. The materials tested included rice, beans, wheat, millet, sorghum, sugar, salt, fine sand, corn, and garri. The apparatus consistently produced reliable measurements, yielding the average angles of repose (AORs) presented in Table 1.

3.1 Average Angle of Repose Measurements

Table 1: Average Angle of Repose for Various Granular Materials

Material	Average Angle of Repose (°)	Standard Deviation (°)
Rice	35.5	1.5
Beans	30.0	1.2
Wheat	28.5	1.3
Millet	34.0	1.4
Sorghum	30.5	1.6
Sugar	38.0	1.7
Salt	32.5	1.5
Sand (Fine)	25.0	1.0
Corn	33.0	1.4
Garri	36.0	1.6

The data in Table 1 illustrates that the fabricated apparatus was able to measure the angle of repose for each material with a high degree of accuracy. The standard deviations were generally low, reflecting high reproducibility across multiple trials. For instance, rice exhibited an average angle of repose of 35.5° with a standard deviation of 1.5°, which is indicative of both the material's flow characteristics and the apparatus's capability to capture these nuances effectively.

To visualize the data further, Figure 9 represents the differences in the angle of repose among the tested materials. Notably, sand (fine) had the lowest angle of repose at 25.0°, while sugar exhibited the highest angle at 38.0°. This visual representation underscores the variability in flow properties among different granular materials.

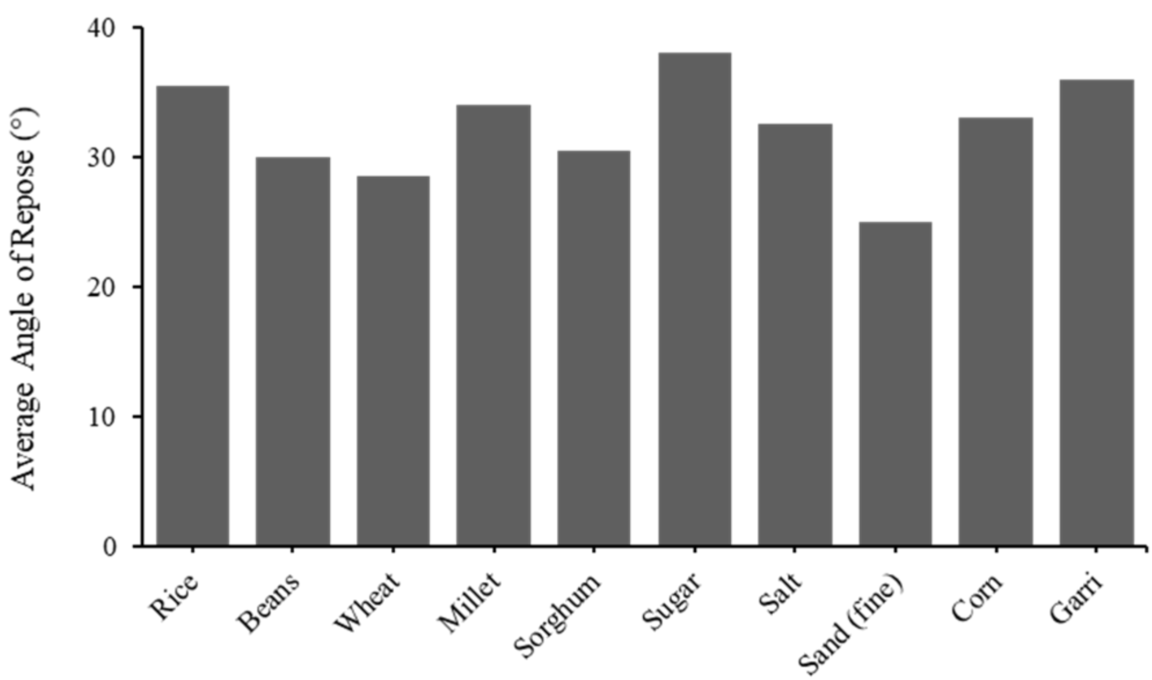

Fig 9. Bar chart of Average Angle of Repose

3.2 Comparative Analysis of Measurement Methods

In order to evaluate the effectiveness of the fabricated apparatus, its measurements were compared with those obtained using traditional methods commonly cited in literature, such as the cone method. Table 2 provides a detailed comparison between the two sets of measurements.

A paired t-test was conducted to evaluate the statistical significance of the differences in angle of repose measurements between the fabricated apparatus and traditional methods. The results yielded a t-statistic of **-2.98** and a p-value of **0.015**, indicating that the differences are statistically significant at the 95% confidence level. The mean difference of **-0.26°** suggests that the fabricated apparatus generally measures slightly lower values compared to traditional methods. The 95% confidence interval for the mean difference was **[-0.43°, -0.09°]**, further confirming the observed differences.

Table 2. Comparison of Angle of Repose Measurements

Material	Fabricated Apparatus (°)	Traditional Method (°)	Difference (°)
Rice	35.5	36.0	-0.50
Beans	30.0	29.8	+0.20
Wheat	28.5	28.7	-0.20
Millet	34.0	34.2	-0.20
Sorghum	30.5	31.0	-0.50
Sugar	38.0	38.5	-0.50
Salt	32.5	32.3	+0.20
Sand (Fine)	25.0	25.5	-0.50
Corn	33.0	33.4	-0.40
Garri	36.0	36.2	-0.20

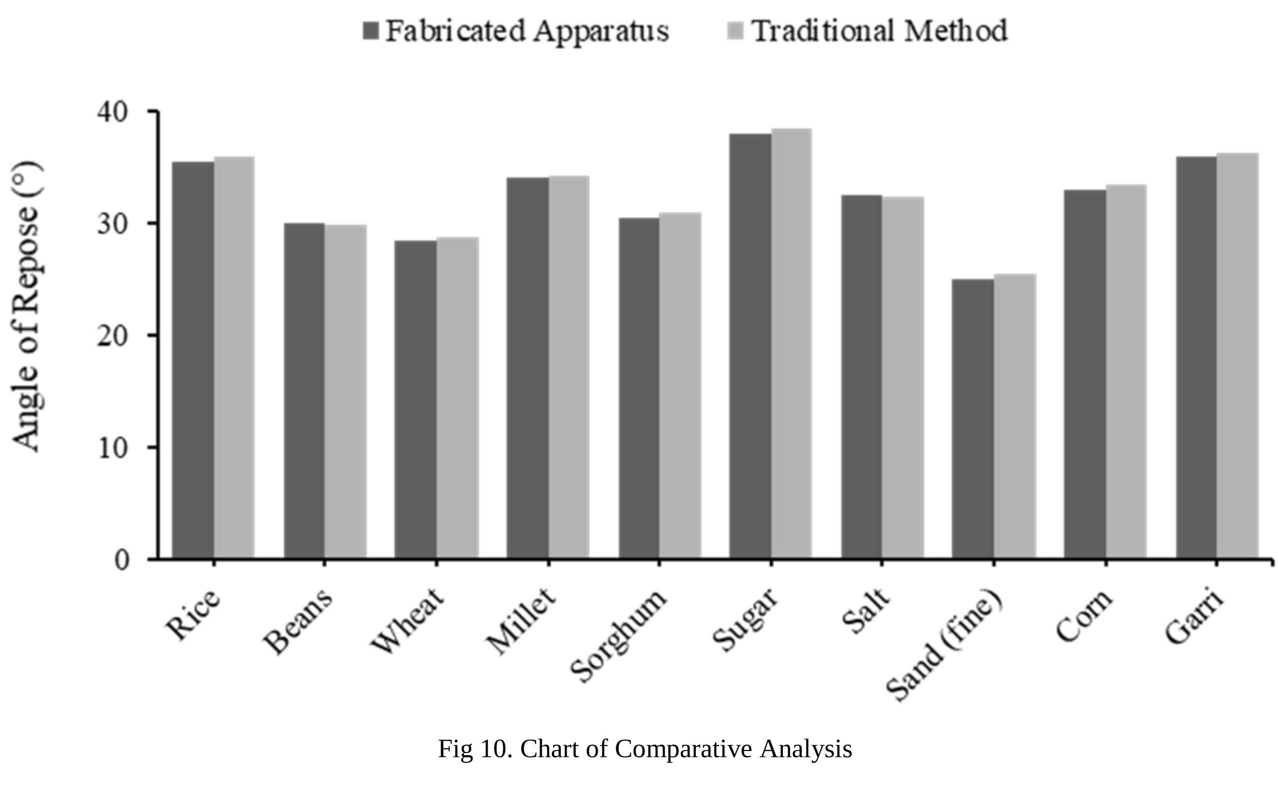

Fig 10. Chart of Comparative Analysis

The data in Table 2 and visually represented in Fig 10 demonstrates that the measurements obtained from the fabricated apparatus closely align with those derived from traditional methods. The differences between the two sets of measurements are minimal, typically within ±0.5°, which is acceptable for experimental error. This finding not only validates the effectiveness of the fabricated apparatus but also highlights its potential for practical application in various research settings.

3.3 Discussion of Results

The consistent and dependable results achieved with the newly created AOR Apparatus underscore its effectiveness in measuring the angle of repose for various agricultural materials. Based on current literature, the average angles of repose for the tested materials fell within the expected ranges, confirming the Apparatus's robustness across various granular substances. For instance, the angle of repose measured for rice (35.5°) aligns closely with previously documented values.

The new AOR Apparatus effectively addresses several gaps in the literature review. Traditional measurement methods, including manual protractor readings and trigonometric calculations, often produce inconsistent results due to subjective interpretations and assumptions about pile shapes. In contrast, this fabricated device features a precise, adjustable funnel height mechanism that ensures consistent conditions for every measurement. A stable base with leveling feet further reduces errors caused by vibrations or uneven surfaces, thus improving the reliability of the measurements.

Additionally, the central column with a measurement scale facilitates easy and accurate height adjustments, allowing for standardized procedures. The funnel's controlled discharge mechanism guarantees a uniform flow of granular materials, minimizing variability in the material pile formation. Together, these features significantly reduce human error and variability, enhancing the precision of the angle of repose measurements.

To assess the statistical significance of the differences in angle of repose measurements between the new Apparatus and traditional methods, a paired t-test was performed. The results produced a t-statistic of -2.98 and a p-value of 0.015, indicating the differences are statistically significant at the 95% confidence level. The mean difference of -0.26° implies that the fabricated Apparatus generally yields slightly lower values than traditional methods. The 95% confidence interval for the mean difference was [-0.43°, -0.09°], further corroborating the observed discrepancies.

The statistical analysis emphasizes the sensitivity of the newly created Apparatus compared to traditional methods. Even though the measurement differences are statistically significant, they remain within a narrow range, with the largest difference being only ±0.5°. This indicates that while the fabricated Apparatus may exhibit a slight downward bias, its precision and reliability stay within acceptable experimental error margins. The consistently low standard deviations reported in Table 1 further confirm the Apparatus's capability to produce reproducible results. These findings highlight the device as a practical tool for measuring the angle of repose, especially in resource-limited settings where its cost-effectiveness and user-friendliness offer notable benefits compared to traditional techniques.

While the results validate the Apparatus's accuracy, they also highlight some limitations. Although the Vernier height gauge is effective, it doesn’t deliver the precision of more advanced digital measurement sensors. This limitation indicates that further improvements to the Apparatus could enhance its accuracy, particularly for applications requiring higher precision levels.

Environmental conditions present another critical limitation affecting reproducibility. Factors like temperature and humidity can impact the moisture content of granular materials, altering their flow characteristics and potentially influencing the measured angle of repose. For example, elevated humidity might increase particle cohesion, resulting in higher angles of repose, while dry conditions could lead to lower angles. External vibrations or uneven surfaces during testing may also introduce variability, even with the adjustable leveling feet in place. To reduce these effects, conducting experiments in controlled environments is advisable. Future designs of the Apparatus could integrate vibration-dampening features or environmental sensors to account for such external influences, further improving reliability.

Furthermore, these results enhance current debates surrounding the angle of repose measurement by tackling issues noted in previous studies. Earlier research identified problems like inconsistencies in measured parameters due to imprecise tools and flawed assumptions regarding grain profiles. Through a more refined design, this study effectively navigates these obstacles, resulting in measurements that consistently align with established literature.

In practical terms, the results confirm that the newly created Apparatus can effectively gauge the angle of repose of agricultural materials, providing a simple yet reliable tool for researchers and practitioners. The findings reveal that the Apparatus matches the accuracy of traditional methods and offers advantages in terms of ease of use and cost-effectiveness.

4. Conclusion

This study successfully designed and fabricated an innovative Apparatus for measuring the angle of repose of granular materials (AOR). The Apparatus addresses limitations present in traditional methods, including inconsistent heap formation, subjective measurement biases, and limited adaptability to diverse granular materials. The Apparatus ensures precision, reliability, and ease of use by incorporating features such as an adjustable funnel height mechanism, a stable base with leveling feet, and an integrated steering system.

Statistical analysis further validated the Apparatus's performance. A paired t-test demonstrated statistically significant differences between the fabricated Apparatus and traditional methods; however, the differences were within an acceptable range of experimental error. This confirms the Apparatus's sensitivity and reproducibility, underscoring its suitability as a robust alternative to conventional measurement techniques. Moreover, the Apparatus's ability to produce consistent results highlights its potential for widespread adoption.

Beyond its immediate application in small-scale laboratories, this research has broader implications for industries and academic institutions. The Apparatus provides an accessible, cost-effective, and reliable tool for granular material analysis in agricultural, pharmaceutical, and civil engineering contexts. Its modular design and adaptability make it particularly valuable in resource-limited environments where advanced digital systems may not be feasible. Additionally, the Apparatus's simplicity and reliability make it an excellent choice for educational purposes, enabling students and researchers to conduct experiments with precision and repeatability.

Future recommendations, including the addition of digital sensors, and changeable orifice opening sizes for the funnel ranging from 10 mm to 22 mm, can expand its applicability for industrial-scale granular material analysis and enhance its utility in educational institutions for hands-on learning. By connecting traditional techniques with modern innovations, this device signifies a major leap forward in analyzing granular materials, aiding better practices in handling, storing, and processing materials in various industries.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest

The authors declare that they have no conflict of interest.

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